Directional Dark Matter Searches with the CYGNO Project

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Abstract. The goal of the CYGNO project is to deploy at Laboratori Nazionali del Gran Sasso (LNGS) an high resolution Time Projection Chamber (TPC) with Gas Electron Multipliers (GEMs) amplification and optical 3D readout of an Helium/Fluorine based gas mixture for directional Dark Matter (DM) searches at low 1-10 GeV WIMP masses. The determination of the incoming direction of WIMP particles can in fact offer not only additional handles for discrimination of the annoying backgrounds, but especially an unique key for a positive, unambiguous identification of a DM signal.

1. Introduction

The presence of DM in the Universe is nowadays an established, yet still mysterious, paradigm: deciphering its essence is one of the most compelling tasks for fundamental physics today. Direct DM searches look for very low energy (1-100 keV) nuclear recoils due to the elastic scattering of Weakly Interactive Massive Particles (WIMPs) in the active volume of the detector. The expected WIMP scattering is due to the Earth's relative motion with respect to the galactic halo, that is believed to contain high concentration of DM from measurement of the rotational curves of our Galaxy. This implies that an apparent WIMP wind coming from the Cygnus constellation (the direction towards which our Solar system is travelling in its rotation around the center of the Galaxy) is expected to be observable on our planet. While technological challenging, the determination of the incoming direction of the WIMP particle can provide a correlation with an astrophysical direction that no known background can mimic.

2. Directional Dark Matter detectors and the CYGNO concept

The development of directional DM detectors has mainly concentrated until recent years on low-pressure ($\leq$ 100 Torr) TPCs, in order to produce O(mm) tracks whose direction could be determined. Although inherently challenging, gaseous TPCs constitute the natural approach to directional DM searches, thanks to the inherent 3D tracking capability and the measurement of energy released along the track dE/dx.

More recently, most world expertise in DM directional detection has gathered together in the CYGNUS proto-collaboration, whose goal is to eventually establish a Galactic Directional Recoil Observatory at the ton-scale, that could test the DM hypothesis beyond the Neutrino Floor and measure the coherent scattering of neutrinos from the Sun and Supernovae[1, 2]. The development of CYGNO fits into this context, with the goal of demonstrating the proof-of-principle of the chosen optical 3D approach towards the development of the multi-modular ton-scale CYGNUS experiment. CYGNO peculiarities and distinctive traits are:

- The use of an He:CF_4 gas at 1 bar as target, to provide sensitivity to both Spin Independent (SI) and Spin Dependent (SD) coupling and the best kinematic match for O(GeV) WIMP masses. From SRIM simulation, helium shows a large Quenching Factor (i.e. the reduction factor for the ionisation output of a nuclear recoil compared to that of an electron of the same energy) above 0.8 already at 10 keV, indicating the possibility of low energy threshold. Moreover, He:CF_4 is known to possess very strong secondary scintillation in the visible light spectrum[3], allowing to image the amplified ionisation via optical devices.
- The charge amplification via Gas Electron Multipliers (GEMs), that offers high gas gains combined with high granularity.
- The use of scientific CMOS (sCMOS) sensors to image the 2D track projection on the GEMs amplification plane[4]. These provide high granularity (4M pixels with dimensions 6×6 μm^2) along with low noise and a high sensitivity ($\geq$ 80% quantum efficiency at 600 nm, with single photon sensitivity). Coupled to the proper optics, these sensors can image arbitrary large areas, where the limit is set by the required spatial resolution and energy threshold.
- The addition of fast light sensors (PMTs or SiPM) to exploit the signal time structure to infer tracks extension along the drift direction (ΔZ) with O(100) μm precision. We demonstrated how the combination of the PMT signal with the sCMOS image allows to reconstruct track in 3 dimensions[5], with sensitivity to track sense through dE/dx measurement.

3. Development towards the CYGNO experiment

To study the performance of the 3D optical readout approach, we developed the LEMOn prototype, shown in left panel of Fig. 1. It comprise of a 7 L active volume (A), with 20 $\times$ 24 cm^2 triple thin GEMs amplification and a meshed cathode at 20 cm drift distance. The drift field uniformity is guaranteed by 20 elliptical silver rings with a 1 cm pitch, forming the field cage. The light produced in the amplification process in the GEMs is read by a PMT[1] beyond a plexiglass windows (B), and imaged by an ORCA Flash 4.0 sCMOS sensor[2] equipped with a Schneider lens[3] (D) downstream to an adjustable bellow (C).

We studied the response to an ^{55}Fe radioactive source (5.9 keV X-rays with an activity of $\sim$ 100 Bq) positioned between two field cage rings at 18 cm drift distance from the GEMs plane, to determine the energy threshold in He:CF_4 at 1 bar in a 60:40% ratio. The data were

[1] Photonics XP3392, 5 ns rise-time, 76mm square-window
[2] For more details visit www.hamamatsu.com
[3] 25 mm FL, 0.95 aperture

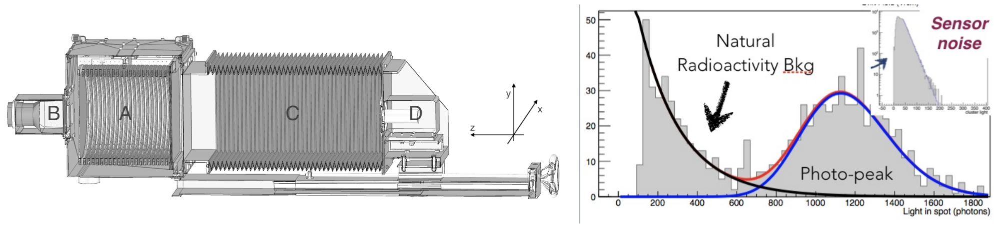

Figure 1. Left: sketch (not in scale) of the LEMOn prototype. In particular, the elliptical field cage (A), the PMT (B), the adaptable bellow (C) and the CMOS camera with its lens (D) are shown. Right: Distribution of number of counting per ^{55}Fe cluster for a run taken with V_{GEM} = 450 V, E_d = 600 V/cm and E_t = 2.5 kV/cm

collected with the sCMOS camera in free running mode (i.e. no trigger signal) and an exposure of 100 ms. In order to characterise the sensor electronic noise, we studied the distribution of the number of pixel countings for *ghost* (i.e. fake) clusters reconstructed in data acquired with the camera shutter closed (inset of right panel of Fig. 1). We then compared this to the photo-peak distribution of real ^{55}Fe events in our data, where we detect 1 photon every 5 eV released in the gas (right panel of Fig.1). From this, we define our energy threshold in terms of probability of reconstructing a maximum number of ghost-cluster per year. Requiring less than 10 ghost/year correspond to a 2 keV energy threshold[6]. By visual inspection of such *ghosts*, is it easy to see how pattern recognition algorithms can easily reject a significative part of this contribution, effectively lowering the energy threshold estimated in this way.

Gaseous TPCs for rare event searches typically lack of the possibility of defining the start time of the event t_0, and therefore to localise the tracks along the drift direction (Z). The importance of an absolute Z measurement resides in the observation that a significant part of the background is localised on the walls of the detector, hence impossible to shield, and passible to rejection only if the full 3D localisation of the event is measured (i.e. fiducialization). We studied the possibility to exploit the track diffusion to estimate the absolute Z event position, as done by[7] with a charge pixel readout. We found that the transverse light profile has a gaussian shape with the total amount of light being proportional to $\sigma_{light} \times A_{light}$ (where σ_{light} is the sigma and A_{light} is the amplitude of the gaussian). We experimentally demonstrated that the ratio $\eta_{light} = \sigma_{light}/A_{light}$ increases linearly with the drift distance and can be therefore used to evaluate the absolute Z with about 20% uncertainty over 20 cm drift distance[8].

We performed a test at the Frascati Neutron Generator (FNG) facility at the ENEA Laboratory to verify LEMOn response to low energy neutrons. FNG uses a deuteron beam on a deuterated target to produce 2.5 MeV neutrons through the D(d,n)^{3}He fusion reaction, with a rate of about 1×10^8 neutrons/s. While a quantitative analysis of the performances is still on-going, we observed several events consistent with nuclear recoils from the topology and the energy density deposit down to tens of keV$_{nr}$.

4. CYGNO PHASE-1 detector concept and expected sensitivity

The CYGNO project final aim is to build and operate a high resolution gas TPC detector at the 50 kg scale for the directional search of a DM signal, in underground LNGS (CYGNO PHASE-2). In order to achieve this very demanding goal, we are going to firstly develop a 1 m^3 volume, O(1) kg mass demonstrator based on the concepts discussed in Sec.2 (CYGNO PHASE-1). PHASE-1 goal is to prove the potentialities and scalability of the experimental approach for near future directional Dark Matter searches at low WIMP masses and neutrino measurement, while at the same time testing innovative techniques and methods to reach the 50 kg scale.

We developed a preliminary GEANT4 based MonteCarlo simulation to study backgrounds

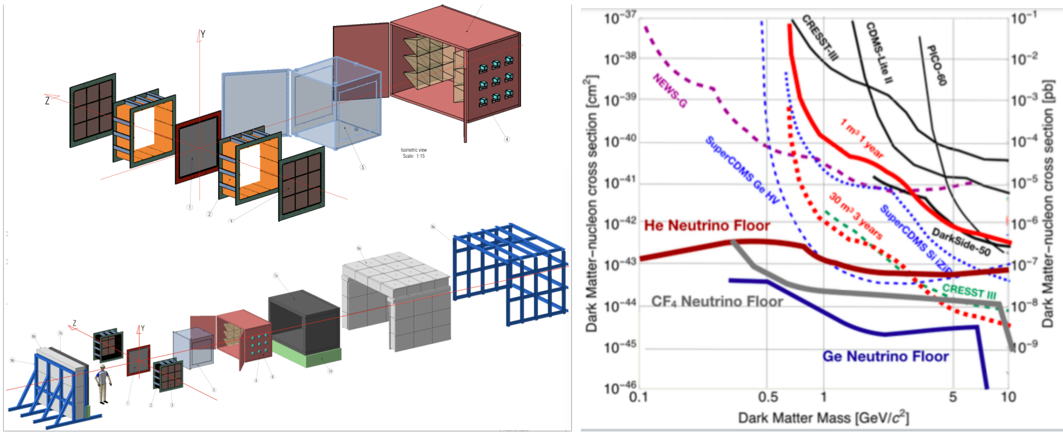

Figure 2. Left: schematic design of CYGNO PHASE-1 internal volume and external shielding. Right: Preliminary expected CYGNO PHASE-1 and CYGNO PHASE-2 sensitivity for 1 year and 3 years data taking respectively and zero background (see text for details).

and to optimise the choice of design, shielding and materials. We first studied the effect of the diffused environmental γ background, simulating different configuration of external passive shielding with layers of Cu, Pb and H_2O, and the goal of less than 10^4 γs/year interacting in the target gas between 0 and 20 keV. The choice of this benchmark is backed up by indication from measurements[9] and simulation within the CYGNUS collaboration[2] that a TPC with 3D readout can reach a 10^5 γs/year rejection factor at O(keV). We preliminarily identified two configurations able to suppress the rate of γ interaction below the required level. A compact solution comprise of (going inwards) 50 cm of H_2O, followed by 15 cm of Archeological Pb, followed by 5 cm of Cu. Similar suppression can be achieved renouncing to the Archeological Pb and increasing the H_2O layer to 250 cm. Further optimisation of this scheme is under way. We identified the largest internal γ background to be produced by the sCMOS cameras and we are exploring various shielding as well as alternative camera body design options to mitigate this. A schematic design of CYGNO PHASE-1 internal volume and external shielding is shown in top and bottom left panel of Fig.2. The preliminary expected CYGNO PHASE-1 (full red line) and PHASE-2 (dashed red line) sensitivity for 1 year and 3 years data taking respectively and zero background, with 1 keV$_{nr}$ threshold on He, 2 keV$_{nr}$ on C and 3 keV$_{nr}$ on F, compared to published limit (full black lines) and future expected limits (coloured dashed lines) is displayed in right panel of Fig.2.

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